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Influence of water ice clouds on Martian tropical atmospheric temperatures

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[1] The Reanalysis derived from the UK Mars general circulation model assimilation of Thermal Emission Spectrometer temperature and dust opacity retrievals at present provides the best estimate of the evolving state of the Martian atmosphere over the course of the Mars Global Surveyor mapping mission. A Control simulation has also been carried out using the same evolving dust distribution as the Reanalysis, but without the temperature assimilation. Differences in zonal mean temperatures between these two simulations reflect possible biases in the representation of dynamical and radiative forcing in the assimilating model. We have identified a cold bias in the Control simulation of tropical temperature which develops in the northern hemisphere summer solstice season. We attribute this bias to the absence of radiatively active water ice clouds in the model and show that clouds likely play a prominent role in shaping the vertical thermal structure of the tropical atmosphere during this season. **Citation:** Wilson, R. J., S. R. Lewis, L. Montabone, and M. D. Smith (2008), Influence of water ice clouds on Martian tropical atmospheric temperatures, *Geophys. Res. Lett.*, *35*, L07202, doi:10.1029/2007GL032405.

1. Introduction

[2] Recently the technique of data assimilation has been used to derive a self-consistent set of thermal and dynamic fields suitable for detailed investigations of various aspects of the Martian circulation system. The Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) has yielded atmospheric temperature profiles with unprecedented latitude and longitude coverage that has provided the basis for characterizing the seasonal evolution of atmospheric temperature [*Smith*, 2004]. The TES retrievals of temperature and dust column opacity have been used as input to the UK Mars data assimilation system to derive the current best estimate of the evolving state of the Martian atmosphere during the MGS mission [*Montabone et al.*, 2005, 2006; *Lewis and Barker*, 2005; *Lewis et al.*, 2007]. We refer to this data set as the MGS Reanalysis. The TES temperature data effectively serve as an external "forcing" to supplement the radiative and dynamical forcing already present in the Mars general circulation model (MGCM) to maintain, as needed, consistency between the simulated evolution of the thermal field and the available observations. A Control simulation has also been carried out using the same evolving dust distribution as the Reanalysis, but without the temperature assimilation. Differences in zonal mean temperatures between these two simulations reflect biases in the representation of dynamical and radiative-convective forcings in the MGCM. Model bias is anticipated to result from missing or incomplete incorporation of physical processes, as well as errors in the specification of the vertical distribution and radiative properties of aerosols.

[3] MGCM simulations have indicated that water ice clouds play an important role in the Martian water cycle [*Montmessin et al.*, 2004] through their influence on water transport via sedimentation. A tropical water ice cloud belt is particularly prominent during the northern hemisphere (NH) summer season [*Clancy et al.*, 1996; *Smith*, 2004]. Recent studies have indicated that accounting for the radiative effects of water can provide a consistent description of aspects of the vertical structure of tropical temperatures [*Hinson and Wilson*, 2004] and the seasonal behavior of nighttime tropical surface temperatures [*Wilson et al.*, 2007]. While the UK MGCM used for the assimilation experiments to date does not incorporate water ice clouds, we can investigate the model temperature bias for evidence of cloud radiative effects that are absent in the Control simulation. We have also compared GFDL MGCM simulations with and without radiatively active water ice clouds to aid in identifying the possible influence of radiative effects on atmospheric temperature.

2. Data and Analysis

[4] The MGS Reanalysis was produced by assimilating the TES temperature and column dust opacity retrievals into the UK MGCM to produce a physically self-consistent record of all atmospheric variables archived at a 2 hour interval over the entire MGS mapping period covering roughly three Martian years [*Montabone et al.*, 2006]. The assimilation is conducted using a modified form of the sequential Analysis Correction scheme [*Lorenc et al.*, 1991] with parameters tuned for the specific case of Mars. Details of the technique are summarized by *Lewis et al.* [2007]. The assimilation uses the observed dust column opacity, updated wherever and whenever TES observations are available, with a vertical distribution which is prescribed as a function of season and latitude [*Montabone et al.*, 2006]. Our focus will be on the spatial and seasonal variation of the zonally-averaged temperature bias ($\Delta T = T_{Reanalysis} - T_{Control}$), where positive ΔT reflects a cold bias in the Control simulation. Uncertainty in the depth of the dust distribution is one significant contributor to temperature bias. For example, we have found that the current specification of an overly deep dust distribution in the polar regions is a major source of a warm polar temperature bias

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in the equinoctial seasons. Dust distribution does not, however, easily account for the cold tropical bias in the NH summer, which is better explained by a lack of water ice clouds in the Control simulation.

3. Zonal Mean Atmosphere

[5] The seasonal evolution of the zonally-averaged equatorial temperature bias over the course of the MGS mapping mission is shown in Figure 1a. Gaps along the time axis represent periods when TES retrievals were unavailable. In these periods, the atmospheric state in the Reanalysis rapidly relaxed back (on the order of a couple of sols) towards that of the Control simulation. The variable depth (half-height, $q = q_o/2$, from *Montabone et al.* [2006, equation (1)]) of the assumed tropical dust distribution is indicated by the white contour. The black contour shows the 185° K isotherm. which reflects the seasonal march in solar forcing and the additional effects of episodic dust storms. The 2001 global dust event is particularly prominent at L_s = 187° in the second year (MY25), while regional storms are present before and after NH winter solstice in each year [*Smith*, 2004]. The cloud condensation level (CL) can be calculated from the TES water vapor column [*Smith*, 2004] and atmospheric temperatures by assuming a uniform vertical mixing ratio. The resulting zonally-averaged CL is shown in red in Figure 1a. There is a clear seasonal progression in the equatorial bias field, with a downward and generally increasingly cold bias trend in the Control (the Reanalysis is warmer than the Control) in the L_s = 45–135° periods in all 3 years. Figure 1b shows that the seasonal variation in the 0.5 hPa cold bias pattern is robustly present throughout low and middle latitudes. The latitude-height structures of the temperature and bias fields at L_s = 120° (MY25) are shown in Figure 2.

[6] A comparison of the temperature bias field with the seasonal variation of equatorial dust and water ice opacity shown in Figure 1c reveals a strong correlation with the tropical water ice cloud belt. By contrast, the 0.5 hPa bias field (apart from the polar regions) shows weak dependence on dust opacity, and suggests that the Control has a relatively consistent warm bias of 2 to 4 K in the seasons without prominent tropical water ice clouds. The most prominent periods of warm temperature bias occur during the L_s = 150–360° seasons of MY24 and MY26, while a smaller warm bias characterizes the generally dustier winter season of MY25. Variations in the response of the bias field to dust are most strongly tied to episodic dust events, and are most likely due to changes in dust depth and particle size distribution not reflected in the MGCM. The correlation of the midlevel (0.2–1.0 hPa) cold bias with tropical ice cloud opacity and the tendency for the cold bias pattern in Figure 1a to track the 185°K isotherm (and the CL) suggest that ice cloud radiative effects, which are not incorporated in the MGCM, might yield the heating implied by the TES temperature "forcing" present in the Reanalysis. While it is possible that the relatively warm Reanalysis temperatures could be accounted for by a deeper dust distribution in the Control simulation, this would seem unlikely given that the implied warming occurs well above the derived condensation level so that aerosol would be expected to be present only in the form of ice-coated dust nuclei. The CL is a strong function of temperature and is less sensitive to the assumed local water vapor mixing ratio. For example, a four-fold decrease in the midlevel mixing ratio leads to the CL rising from 3 hPa to 2 hPa.

[7] Figure 2b shows that the TES temperature forcing in the NH summer solstice season (L_s = 120°) results in warmer temperatures in the Reanalysis compared to those in the Control. This difference reflects both the effects of water ice clouds and other model biases. We have attempted to isolate the temperature effect attributable to clouds by contrasting the bias fields for relatively clear and cloudy seasons. For example, Figure 2c shows the difference between ΔT evaluated at L_s = 120° and L_s = 0° (MY25). The differencing is restricted to low latitudes due to strong seasonal variations in the bias field at higher latitudes (see Figure 1b). Figure 2c suggests that the vertical structure of the tropical cloud effect is non-negligible above 2 hPa and peaks at around 0.5 hPa. This is consistent with the 6–8 K seasonal variation in equatorial 0.5 hPa temperature evident in Figure 1a.

[8] We now consider the radiative influence of water ice clouds in an independent MGCM. Figures 3a and 3b show the zonal mean temperature fields at L_s = 120° for the two simulations described by *Wilson et al.* [2007], with and without radiatively active clouds, respectively. These simulations were carried out with the GFDL MGCM, using a uniform dust column opacity of 0.15, which is appropriate for the season. The aspect of particular relevance here is that the cloud simulation has daytime and nighttime ice cloud opacities consistent with the TES IR retrievals and the greenhouse effect on surface temperature, respectively. Moreover, as discussed by *Wilson et al.* [2007], the inclusion of clouds yields tropical temperature profiles comparable to those derived from MGS Radio Science occultations [*Hinson and Wilson*, 2004]. Here, we find that radiatively active clouds notably improve the GFDL simulation of NH summer solstice temperature as indicated by the close agreement between Figures 2a and 3a. Significantly, the patterns of temperature enhancement attributed to the influence of radiatively active clouds are quite consistent. This suggests that cloud radiative effects can plausibly account for the latitudinal distribution and amplitude of atmospheric temperature warming evident in the Reanalysis-Control difference shown in Figure 2c. One effect of the tropically confined water ice clouds is to intensify the Hadley circulation, which results in adiabatic heating at high latitudes in the winter hemisphere, beyond the direct radiative influence of the clouds.

[9] Additional simulations show that the temperature enhancement is insensitive to changes in solar averaged cloud single scattering albedo, ω, ranging from 0.98 to 0.995, indicating that the radiative influence is dominated by IR effects rather than shortwave absorption, which varies as $1-\omega$. Notably, reducing the dust column opacity from 0.15 to 0.05 yields the same temperature distribution as in Figure 3a, indicating that clouds dominate the radiative forcing in the simulation of this season.

4. Thermal Tides

[10] We have also examined the atmospheric temperature and surface pressure response to semidiurnal solar forcing to gain insight into the extent of the vertical heating in the

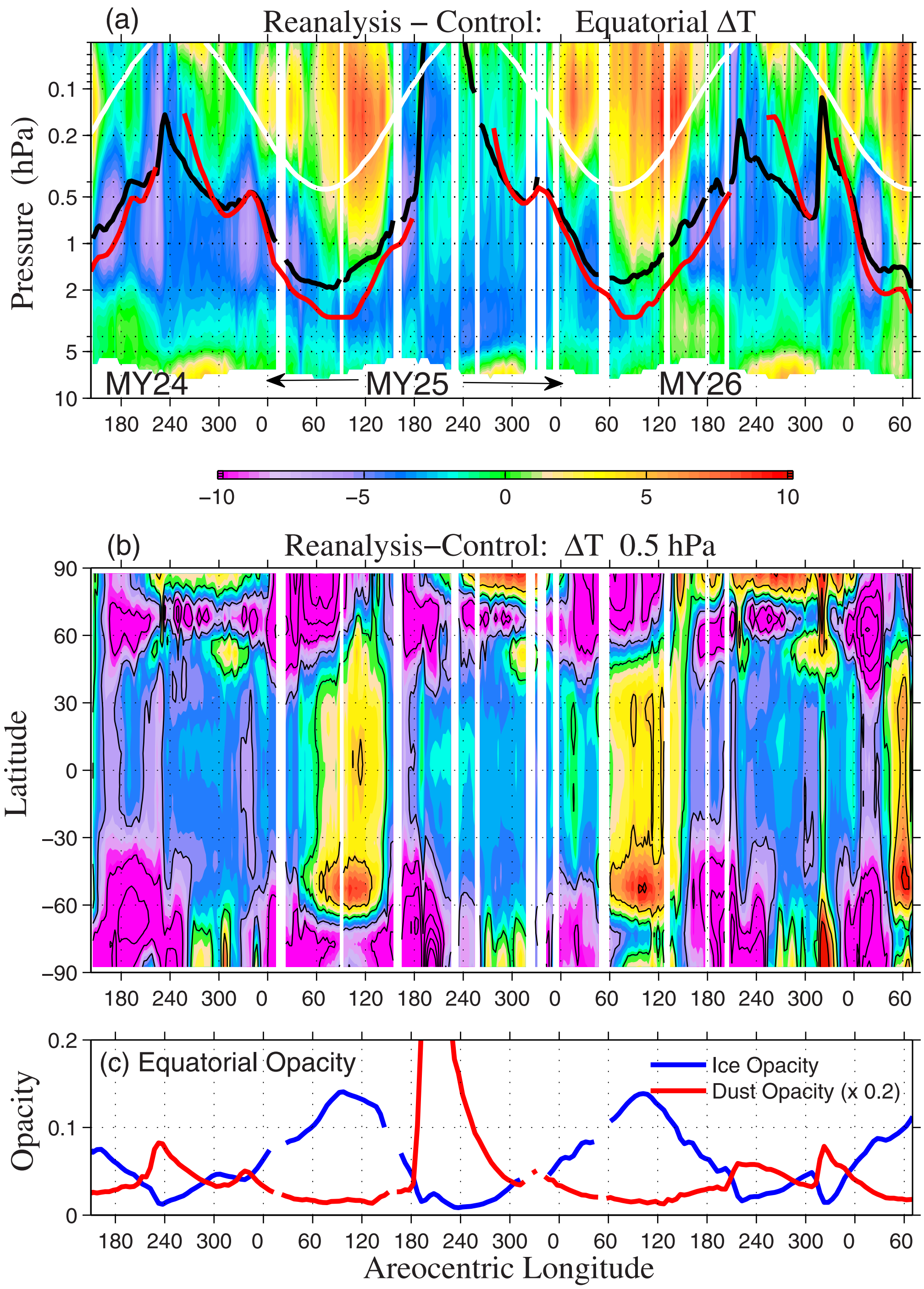

Figure 1. (a) The seasonal evolution of the zonally-averaged equatorial temperature bias ($\Delta T = T_{Reanalysis} - T_{Control}$) over the course of the MGS mapping mission. The variable depth of the assumed dust distribution is indicated by the white contour. The black contour shows the 185° K isotherm. The red contour indicates the approximate height of the cloud condensation level. (b) The seasonal evolution of zonally-averaged temperature bias at 0.5 hPa. The contour interval is 5 K. (c) The seasonal evolution of zonally-averaged equatorial dust column opacity (red) and water ice cloud column opacity (blue). Note that dust opacity is scaled by 0.2.

assimilation. The sun-synchronous semidiurnal tide (S_2) is characterized by a meridionally broad, vertically propagating gravity wave with a vertical wavelength of ~100 km. As a consequence, the semidiurnal surface pressure response, $S_2(p_s)$, is an effective measure of vertically integrated thermal forcing. Figure 4 shows the seasonal variation of equatorial $S_2(p_s)$ for the Reanalysis and Control simulations. They are both very similar and are highly correlated with the dust opacity, as is discussed by *Lewis and Barker* [2005]. We also show the seasonal evolution of $S_2(T_{15})$, the semidiurnal component of depth-weighted temperature centered at 0.5 hPa. The amplitude of this signal is representative of

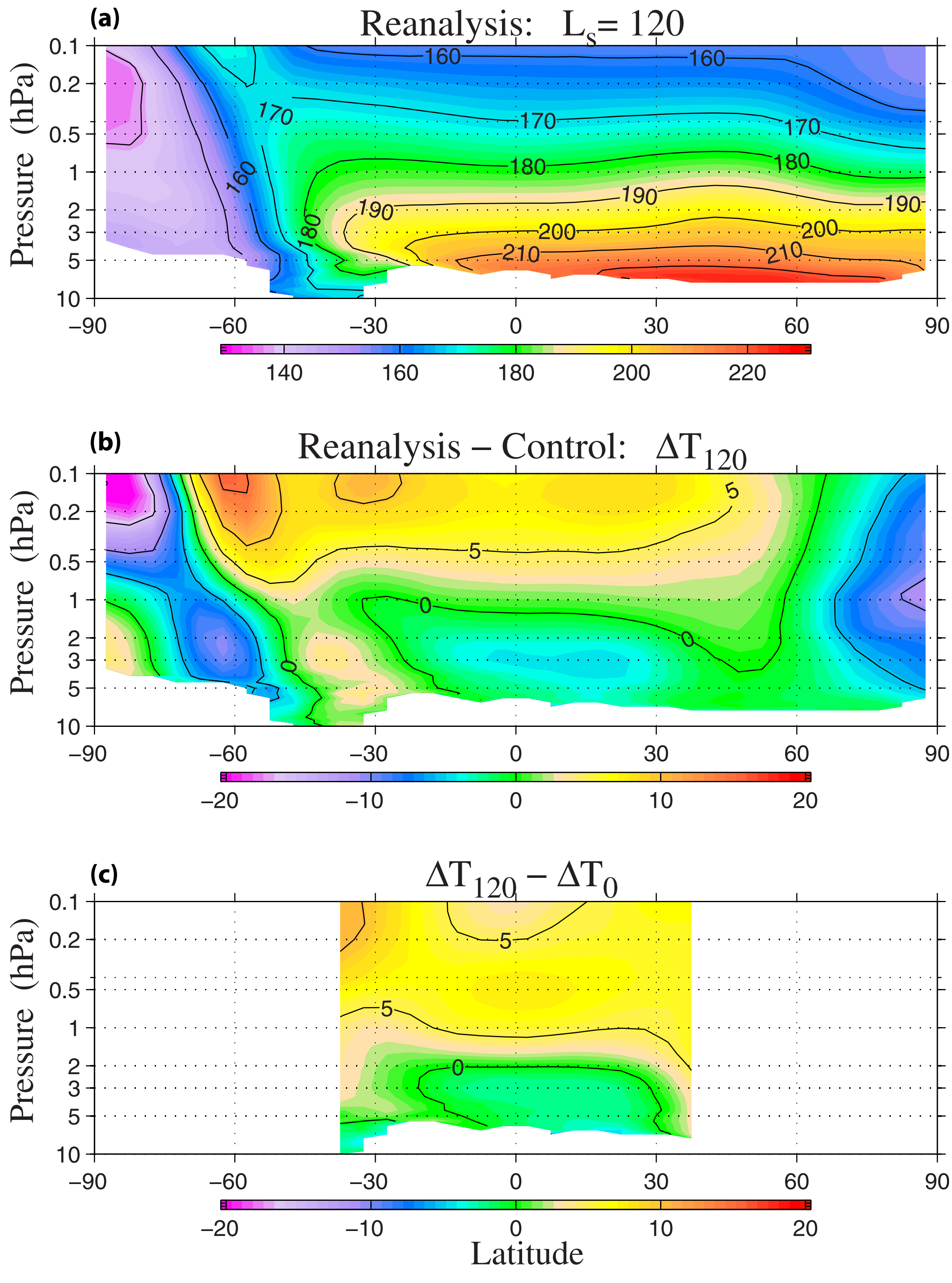

Figure 2. (a) The zonal mean Reanalysis temperature distribution for NH summer (L_s = 120°). (b) The corresponding temperature bias field, ΔT. This field reflects the influence of both water ice clouds and the effects of other model bias, as discussed in the text. (c) The difference in ΔT evaluated at L_s = 120° and L_s = 0° (MY25).

the strength of the tide forcing in a layer centered at 0.5 hPa, rather than integrated over the full column as is the case for $S_2(p_s)$. Note that there is greater relative variation in $S_2(T_{15})$ between the Reanalysis and Control simulations than is present between the two $S_2(p_s)$ signals. We suggest that this reflects the seasonally evolving differences in the depth of thermal forcing between the two simulations. It is particularly striking that the amplitude of $S_2(T_{15})$ in the Reanalysis increases (doubles) between L_s = 45° and L_s = 110°, while that for the Control remains unchanged. Furthermore, the amplitude of $S_2(T_{15})$ in the Reanalysis subsequently decreases between L_s = 135° and L_s = 150°, while the

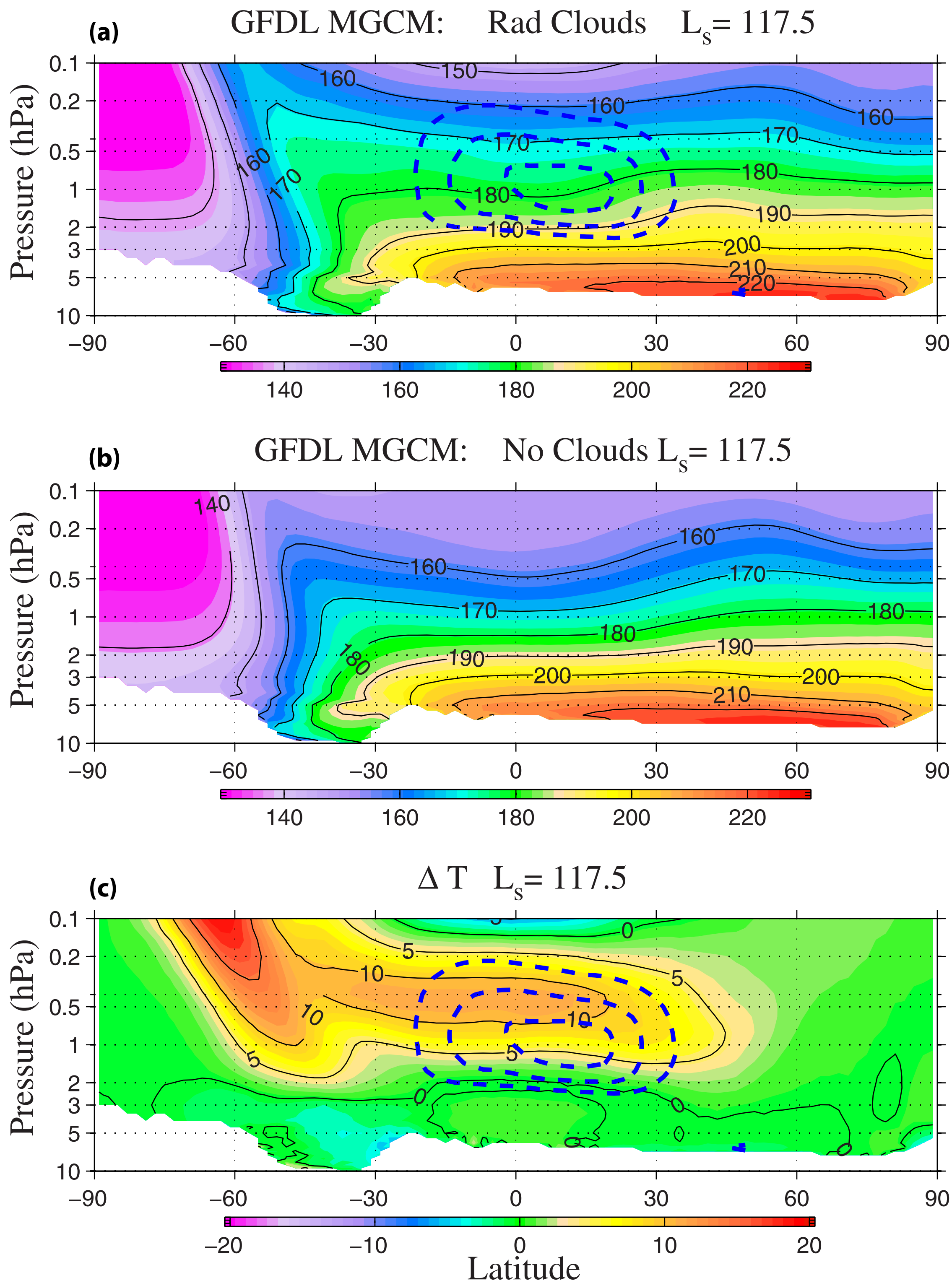

Figure 3. The zonal mean temperature distribution for the GFDL MGCM simulations (a) with cloud radiative effects and (b) no cloud effects and (c) the difference temperature. Dashed contours indicate the location of the simulated tropical cloud belt, with a contour interval of 10 ppm.

amplitude in the corresponding Control run increases, as is consistent with increasing dust opacity and solar radiation. The amplitude of $S_2(T_{15})$ for the Control simulation remains notably stronger than that for the Reanalysis from $L_s = 145°$ to the start of significant dust storm activity ($L_s \sim 225°$ in MY24 and MY26, and $L_s = 187°$ in MY25). We interpret these trends as follows: The cloud contribution to radiative forcing at 0.5 hPa that is implicit in the Reanalysis dominates the dust-only forcing (Control) in the period roughly centered about NH summer solstice. The relatively strong

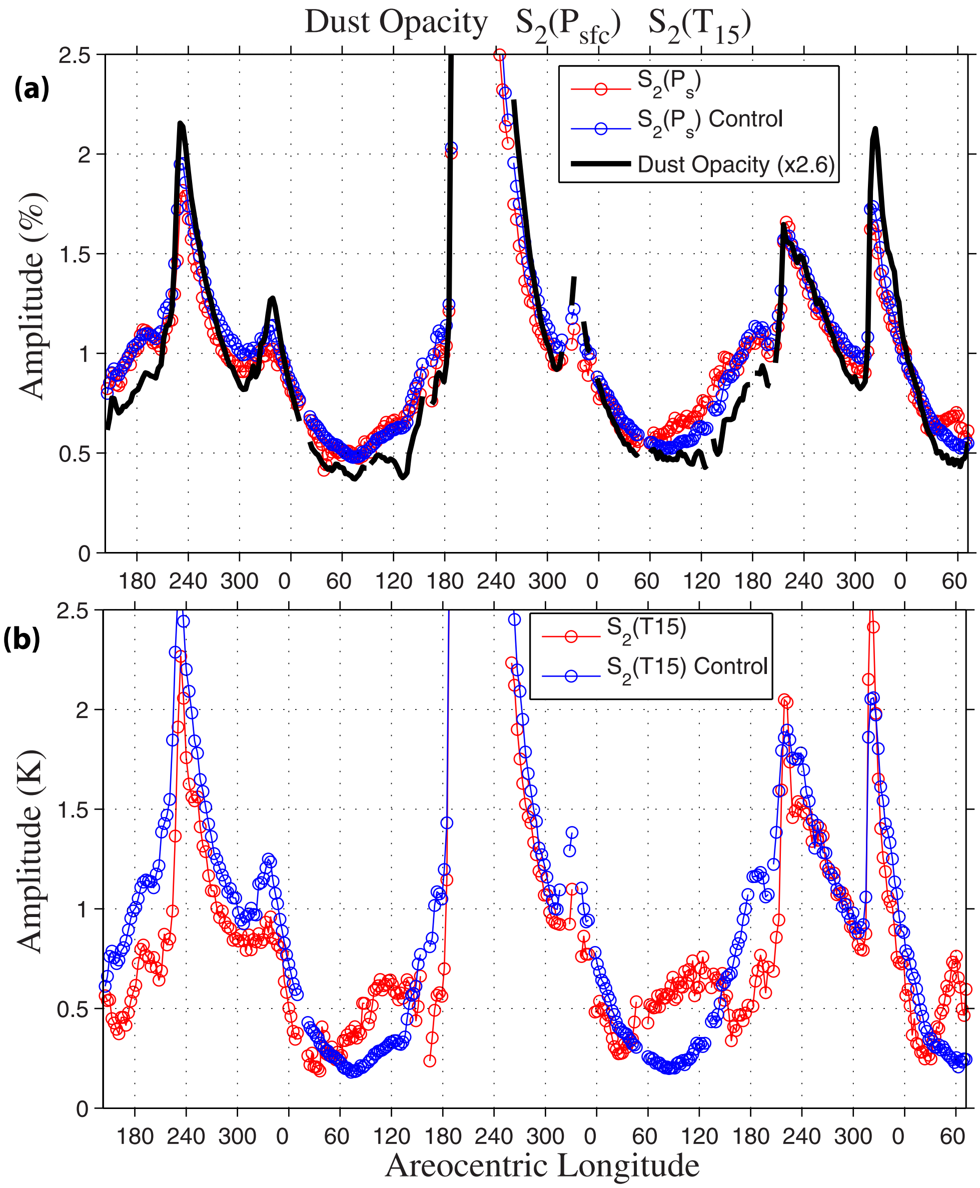

Figure 4. (a) The seasonal variation of equatorial dust opacity compared with the amplitude of the sun-synchronous semidiurnal component of normalized surface pressure, $S_2(P_s)$ for the Reanalysis an Control simulations. Tide amplitude is normalized by the diurnal average pressure. (b) The seasonal variation of $S_2(T_{15})$, where T_{15} is a depth-weighted temperature centered at ~0.5 hPa.

0.5 hPa level forcing after $L_s = 145°$ in the Control suggests that the prescribed dust distribution is too deep for this period. Simulations with interactive dust transport [*Basu et al.*, 2004] indicate that the tropical dust depth becomes shallower as the season progresses from $L_s = 90°$ to 180° as a consequence of the seasonally weakening Hadley circulation, a tendency which is contrary to the prescribed depth evolution used in the assimilation (Figure 1a).

5. Summary and Discussion

[11] We have used the recently derived MGS Reanalysis and its companion Control simulation to carry out a comparison of atmospheric temperatures to look for possible model biases. We have identified a cold bias in the tropical temperatures in the Control that evidently reflects the influence of radiatively active water ice clouds which is not accounted for in the model physics. Independent simulations with the GFDL MGCM indicate that water ice clouds can provide sufficient radiative forcing to account for the observed temperature differences between the UK Reanalysis and Control simulations. Our results add to the evidence that clouds contribute to the radiative forcing in the atmosphere and at the surface. The simulation results shown in Figure 3 indicate that the radiative effects of aphelion season clouds can account for tropical temperature structure [*Hinson and Wilson*, 2004], anomalous nighttime surface temperatures [*Wilson et al.*, 2007] and enhanced zonal mean temperatures above 1 hPa. This consistency provides further support for the radiative influence of ice clouds and highlights the ability of MGCMs, with data

assimilation, to interpret diverse observations as aspects of the same physical process.

[12] It remains to be determined just how cloud forcing drives the observed temperature enhancement. Clouds result in an increase in atmospheric emissivity and are absorbers (despite the strong scattering) of solar radiation. Our simulations suggest that the temperature response to tropical cloud forcing is dominated by the IR influence. We note that the intensity of the Hadley circulation is enhanced when the radiative damping rate (emissivity) is increased [*Haberle et al.*, 1997], resulting in a warming response in the winter hemisphere. We are also investigating the warm polar temperature biases evident in Figure 1b during the equinoctial seasons. GFDL MGCM results indicate that low altitude polar hood water ice clouds can yield significant IR cooling, in contrast to the heating influence of higher altitude tropical clouds.

[13] It is anticipated that the recognition of the radiative role of water ice clouds will motivate further investigation of microphysical processes which influence the nucleation and growth of cloud particles. Particle size affects both cloud optical properties and sedimentation velocity. Sedimentation controls the vertical extent of the clouds. Therefore, the cloud and radiation fields are tightly coupled. The analysis of limb profiles provided by TES, Mars Express, and Mars Climate Sounder will provide significant new insight and constraints on cloud vertical structure.

[14] Our investigation of tide amplitudes and our simulation with reduced dust loading together suggest that cloud influences play a significant, and perhaps dominant, role in determining the vertical structure of the tropical zonal mean temperature during the NH summer season. If so, then dust lifting by dust devil activity may play a less prominent role in the seasonal dust cycle than is currently assumed. In particular, tuning dust lifting parameterizations to fit observed aphelion season temperatures may not be appropriate [e.g., *Basu et al.*, 2004].

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